ANALYSIS OF PARTIAL DISCHARGE SIGNALS USING STOCKWELL TRANSFORM

A THESIS SUBMITTED IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE OF

Master of Technology
in
Industrial Electronics

Submitted by

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Under the Guidance of

Prof. Subrata Karmakar

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CERTIFICATE

This is to certify that the thesis entitled, "**Analysis of Partial Discharge Signals using Stockwell Transform**" submitted by **Saumya Ranjan Swain (Roll No. 213EE5353)** in partial fulfilment of the requirements for the award of Master of Technology Degree in Electrical Engineering with specialization in Industrial Electronics during 2013 - 2015 at the National Institute of Technology, Rourkela is an authentic work carried out by him under my supervision and guidance.

To the best of my knowledge, the matter embodied in the thesis has not been submitted to any other University / Institute for the award of any Degree.

Date-

Prof. Subrata Karmakar
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I am grateful to my guide Prof. Subrata Karmakar for giving me the opportunity to work on this area with vast opportunities. His valuable guidance made me learn some of the advanced concepts during my work. I sincerely appreciate the freedom Prof. S. Karmakar provided me to explore new ideas in the field of my work. He supported and encouraged me throughout the project work.

I render my respect to all my family members for giving me mental support and inspiration for carrying out my research work. My hearty thanks to all my friends for being with me during this work.

Saumya Ranjan Swain

Roll No. 213EE5353

Contents

Abstract

Partial Discharge (PD) is characterized by current pulses that appear in high voltage (HV) electrical equipments obtained from ionization process when damaged insulation is submitted to high values of electric. That means ageing and deterioration is mainly occurs due to the presence of partial discharge in an insulator used in the high voltage power equipments. The process of deterioration develop until the insulation system is unable to withstand which causes sudden failure of live assets often release high amount of energy leading to explosion. So occurrence of PD leads to major problem for both economic and safety implication and its monitoring is most important activity by transmission companies. PD monitoring is a useful method of assessing the aging degree of the insulation, manufacturing defects or chemical/mechanical damage. Many sources of noise (e.g. DSI, random noise gaussian noise and power frequency noise) directly affect the PD estimation. In order to get original PD signal noise has to be removed. So for the extraction of original PD one from noisy, Wavelet transform is used. It can simultaneously give information about occurrence of PD pulse, time and pulse spectrum, and also de-noise PD pulse. Different type wavelets are used for observation and analysis of PD signals in high voltage apparatus in order to get actual PD pulse. Wavelet denoising technique comprises different denoising performance indices for the comparative analysis of the noisy PD signal. But wavelet fails to explain about frequency and phase information of the de-noised signal. So getting the final denoising result Stockwell transform is used for time frequency analysis of the denoised PD signal. The S-transform has an advantage in that it provides multi resolution analysis while retaining the absolute phase of each frequency component of the signal. But it suffers from poor energy concentration in the time frequency domain In present days we are using modified stockwell transform for detection of partial discharge signals. In modified S-transform gaussian window of variable length is used that scales the signal with the frequency to improve energy concentration.

List of Figures

List of Abbreviations

PD	Partial Discharge
CWT	Continuous Wavelet Transform
DEP	Damped Exponential Pulse
DOP	Damped Oscillatory Pulse
DSI	Discrete Spectral Interference
DWT	Discrete Wavelet Transform
FT	Fourier Transform
HV	High Voltage
LWT	Lifting Wavelet Transform
WT	Wavelet Transform
PD	Partial Discharge
QMF	Quadrature Mirror Filter
TFR	Time-Frequency Representation
MSD	Multi-Resolution Signal Decomposition

DEDICATED

TO

MY BELOVED PARENTS

Chapter 1

Introduction

Chapter 1

Introduction

1.1 Introduction

Insulation in electrical system is a main part of HV power apparatus. Despite of the technological advancements, manufacturing of a perfect insulator has been an ideal concept. In reality the insulators are contaminated with various kinds of impurities. It has been studied such as in many cases abasement of insulation is one of the main cause of collapse of HV power system apparatus. Failure of the insulation system in HV equipments while in service leads to some serious problems such as health, environment problems. Hence, this is mandatory to detect the degradation of the insulation earlier, so that remedial measures can be taken. When abasement happens in insulation, by any of the cause, no. of electrical sparks within the insulation are generated which are called as partial discharge (PD) .Therefore partial discharge computation have appear as a powerful tool for insulation system under high voltage stress. Using PD signal analysis the PD behaviour can be defined, and the nature and the seriousness of the degradation can be studied. Nowadays, computer based PD measurements are performed online and onsite to keep the equipment in service while monitoring it. The difficulty involved in such measurements is that the surrounding noise and interferences corrupt the acquired PD signal, causing trouble in the study of the signal. Hence, it is necessary to extract the PD pulses before further processing. Various time and frequency domain de-noising tools are adopted to extract the partial discharge (PD) pulses from extreme high level noises. Now-a-days from various researches it shows that wavelet transform (WT) is a strong tool in denoising PD signals. Partial discharge pulses are irregular, transient and non-periodical in nature. As the WT is an effective tool in analyzing the all type of signals (non-periodic, asymmetrical) in time domain. It is applied to de-noise and analyze features of the partial discharge (PD) signals.Wavelet transform can be operated in both time and frequency domain. The frequency domain approach adopts convolution of the signal with the impulse response of the wavelet filters, whereas time domain approach called lifting wavelet transform employs lifting scheme. Further, the extracted PD signal is examined using S-transform. The FT shows the frequency components of a signal, but fails to show the position of occurrence of the frequencies. The STFT gives the time-frequency spectrum presentation of a signal but possesses a constant resolution. Wavelet Transform (WT) technique shows the time-scale presentation of a noisy signal, which requires interpretation of the scale to frequency domain. S-transform overcomes the above difficulties and gives the time-frequency spectrum presentation of a signal with varying resolutions. Nowadays modified S-transform is used for more accurate results.

1.2 literature Survey

Extensive research works have been pursued in the area of requisition of digital signal processing techniques for analysis of partial discharge signals. Ramu and Nagamani explained the various issues related to PD measurements for condition monitoring of HV equipments. They discussed the processes leading to PD and various electrical methods of PD measurements. They mentioned the different kinds of noise and interferences that affect the PD signals during online and onsite measurement. Also they proposed the WT as a tool to de-noise the PD signals. Ma et al. used the characteristics of the detection circuits to simulate two types of PD signal pulses called damped pulses such as exponential type pulse (DEP) and oscillatory type pulse (DOP). They used correlation coefficient to find out the suitability of wavelets to be used as mother wavelets for the study of the two pulses. They applied WT for extracting the DEP and DOP pulses immersed in noise. Kim and Aggarwal presented the theory of wavelet transform and its advantages compared to the earlier methods like FT and STFT. They proposed the suitability of wavelet for transient signal analysis. Satish and Nazneen proposed a method which is based on wavelet denoising technique for taking out PD signals from noise and spectral interferences. The de-noising method uses reconstructed time domain detail and approximation components to recover the signal in harsh conditions. In the de-noising method the reconstructed components corresponding to the PD pulase signals are kept and others are eliminated. They implemented the denoising technique on simulated practical partial discharge (PD) signals which are distorted by noise and spectral disturbances, and evaluated denoising method using de-noising performance indices. Zhou et al. proposed a method which tends selction of the selected mother wavelet for DWT denoising technique of PD signal. This method calculates the energy distribution of the signal over all the DWT decomposition levels using various wavelets and selects the wavelet which retains most energy in a single level. Stockwell et al. proposed s-transform for time frequency representation of a signal. S-transform is an improved version of WT and STFT. Stockwell presented the derivation of S-transform and mentioned the procedure to implement it.They have generated information about magnitude phase and frequency from the corresponding S-matrix. Sahu proposed a modified Gaussian window based S-transform for the time-frequency analysis of a signal. This proposed scheme improves the time frequency representation resolution. These are used only for the detection of proper partial discharge signals.

1.3 Motivation and Objective of the Work

Extraction of PD signal from severe noise and interferences is the main difficulty in the measurement of PD signals. Among the various de-noising methods used for the extraction of PD signals, wavelet transform based de-noising methods are more powerful. Wavelet transform based de-noising of PD signals is performed in different ways. There are different methods for the selection of mother wavelet, determination of maximum decomposition levels and type of thresholding for thresholding of coefficients. All the methods have their own advantages and disadvantages. Hence, a comparison between the different wavelet based PD signal de-noising techniques is necessary. Further, the de-noised PD signal is processed through various digital signal processing techniques to analyze the PD characteristics. Recent research shows that for the time-frequency analysis of a signal, S-transform is an effective tool. It eliminates the drawbacks of STFT and wavelet transform.So it is clearly known existence of PD signals at what time and frequency by this Modified S-transform.

The main objective of this thesis work is,

- To numerically simulate noisy PD signals having different characteristics.
- To apply different wavelet transform techniques for denoising the simulated a practical PD signal.
- To evaluate the performances of the adopted PD signal de-noising methods.
- To analyze the practical PD signal using S-transform, that will show time frequency representation (TFR) of the PD signal.

1.4 Thesis layout

Chapter 1 reviews the literature on concept of PD, wavelet based PD signal analysis and S-transform based time frequency analysis.

Chapter 2 describes the mechanism of PD in the insulation of high voltage equipments. It also introduces electrical PD measurement. The two types of PD pulses depending on the nature of detection circuits are mentioned and simulated numerically. A practical signal acquired in laboratory is also introduced in the chapter.

Chapter 3 employs DWT based de-noising methods for the extraction of PD signal. The theory of DWT is presented first and then the various issues related to the wavelet based de-noising, like mother wavelet selection, selection of maximum decomposition level, and choosing a proper thresholding rule are mentioned. Various de-noising performance indices used to evaluate PD signal de-noising methods are mentioned. The simulated and practical noisy PD signals are de-noised using the DWT, adopting different wavelet selection methods and thresholding rules.

Chapter 4 employs S-transform for the time-frequency representation of the de-noised practical PD signal.

Chapter 5 summarizes the results obtained in various chapters and the scope for future work is discussed in brief.

Chapter 2

Partial Discharge Concept

Introduction

Electrical Partial Measurement

Partial Discharge Analysis

Simulation of noisy PD signals

Summary

Chapter 2

Partial Discharge Concept

2.1 Introduction

In accordance with international standard the existed Partial Discharge signals can be defined as localized dielectric breakdown which creates partial short circuit in the insulator that present between conductors and conductor surroundings. Simply a PD pulse is either voltage or current pulse found in the high voltage electrical equipments .However the PD present in the insulation reduces the quality of insulation in the electrical equipments. PD is nothing but defects which is present in the insulation matrix which is in the size of submicron level and negligible as compared to the thickness of the insulation. The manufacturing process of insulation system involves stages initially selection and composition of raw materials, after that operation of raw materials, chemical and thermal equipments if required. The total process of giving electrical insulation in HV power apparatus requires participation of material, man and different environmental states. Only for that reason it is so much difficult to attain pure electrical insulation in HV apparatus because it is polluted during the process of manufacturing. Defects in HV apparatus are more critical as they lead to electrical discharge which creates hazardous to human life as well as human sources. So it is more necessary to extract actual PD pulses from the noisy one then give treatment to reduce the effect of electrical discharges.

2.2 Electrical partial discharge measurement

Insulation is an important component of HV power equipments used to diminish the energized conductors at different potentials and high voltage conductors from ground. Insulation in power equipments may also be used for cooling and internal electrical discharge suppression purposes. The insulation can be in any of the three states of matter. It is always desirable to have perfect insulation in electrical equipments. However the defects present in the insulation degrades the quality of the insulation. Defect in insulation is defined as any unintended material included in the matrix of insulation. The presence of defects lowers the quality of the insulation. The size of defects in insulation is generally in sub-micron level and is negligible as compared to the thickness of the insulation. Some of the examples of defects are air bubbles, voids, micro-cracks, improper contact between insulation and conducting surface. Partial Discharge means a spark that bridges a small portion of insulation.

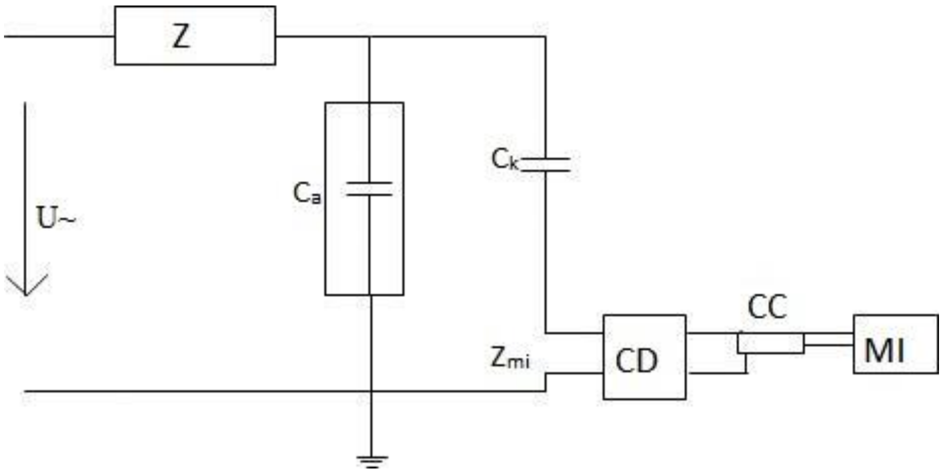


Fig. 2.1(a) Standard set up used for PD measurement

The above figure shows the classical detection of PD in an HV apparatus. In this method electrical pulses are detected which are caused by partial discharge (PD).This is the best method ever used for the experiments.

Here U~ represents high voltage power supply

Z_{mi}-input impedance of the measuring system

CC-Connected Cable

C_a-Gadget to be tested

C_k-Coupling Capacitor

CD-Coupling Device

The coupling capacitor C_k passes the PD current pulses, swelling the computation sensitivity. The impedance Zmi changes the PD current pulses to a corresponding voltage for appropriate augmentation, computation and storage. The electrical PD measurement is mainly employed in high voltage (HV) apparatus. Here coupling device (CD) can be realised by a RLC (resistor, inductor and capacitor) circuit or a RC circuit (resistor and capacitor). RLC circuit is used in small band detection process and RC circuit is used wide band detection process. The detailed diagram is shown in next page.

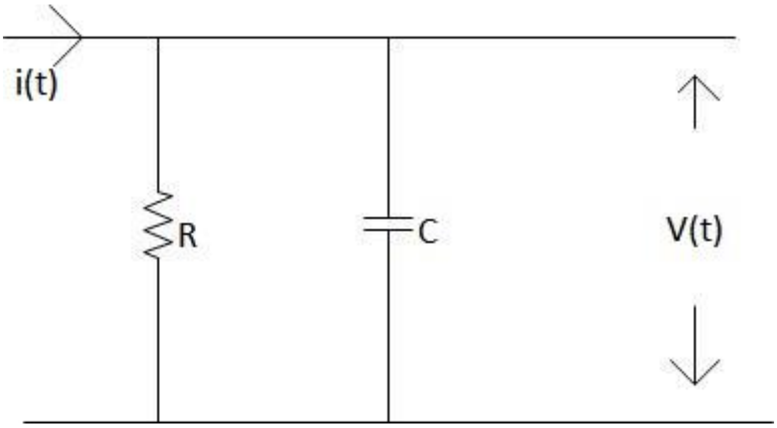


Fig. 2.2(b) PD measurement RC impedance circuit

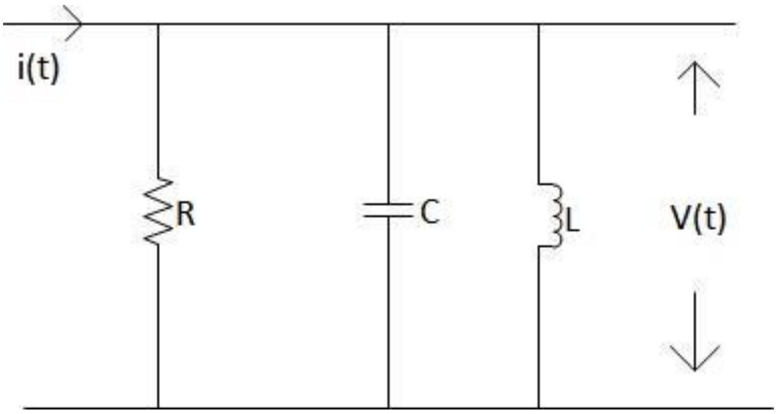


Fig. 2.3(a) PD measurement RLC impedance circuit

2.3 Partial discharge analysis

The main difficulty involved in the PD signal analysis is to independent the PD signal from surrounding noise and interferences present onsite as well as offsite. The two types of interferences that contaminate the PD signals are random internal noise and externally coupled disturbances. Noise results from random fluctuations in electronic devices such as amplifiers, ICs, detection circuit impedance etc. The external interferences are again classified as discrete spectral interferences (DSI), pulse type disturbances which are periodic in nature and provisory pulse shaped type disturbances. The DSI generates from radio transmission and power line carrier systems. The periodic pulse shaped interferences obtained from PE circuits or during continuous switching of adjustable speed thyristor drives provisory pulse shaped type disturbances obtained from exceptional switching operations, friction between tiny contacts etc. For eliminating the noise and interferences from the PD signal various de-noising methods are taken into account. Among the de-noising methods wavelet transform is a strong method in extracting the partial discharge (PD) signals from strong noise and disturbances. Wavelet denoising technique can again be performed using various techniques and each has its own advantage. To evaluate the performance of a de-noising method the reference PD signal or the clean partial discharge (PD) signal should also be known so that the de-noised result can be compared with the reference. In this work also Stockwell transform is passed down for analysis of partial discharge pulse type signals to get the time frequency presentation. It eliminates the drawbacks of both STFT and WAVELET methods of denoising. In this method we can compare the time frequency spectrum of the signal under various noise conditions. It is even more effective tool for non-stationary signal processing. After denoising that signal again used by S-transform for showing time frequency spectrum representation.

2.5 Simulation of noisy PD signals

In electrical measurement, PD signals are taken by passing the current into an observation circuit. So the perceived voltage signals naturally possess electrical pulses shapes which are off different shapes which is depend upon the type of observation circuits. The observation circuits are realized using RLC and RC impedance circuits because of high impedance. The output voltage pulse in RC impedance circuit is characterized as a DEP (damped exponential pulse) and the output voltage pulse in RLC impedance circuit is characterized as a damped oscillatory pulse (DOP). By recognizing the different shape of a PD current pulse and the type of observation circuits,

DOP and DEP will be numerically simulated which is shown below figure.

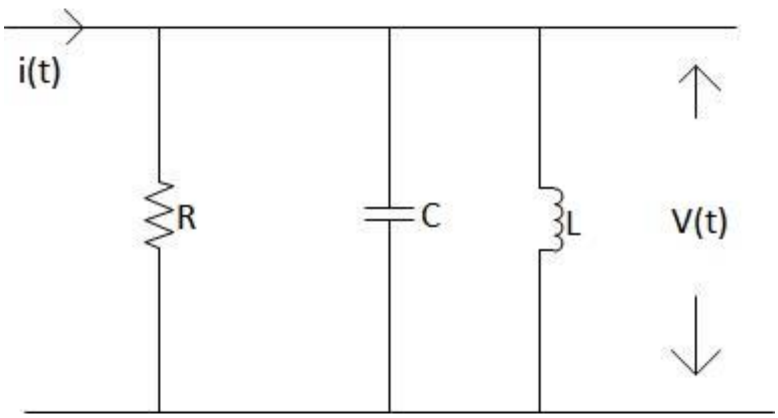


Fig. 2.4(b) PD measurement coupling device (RLC impedance circuit)

By using this circuit DOP pulse can be simulated as below

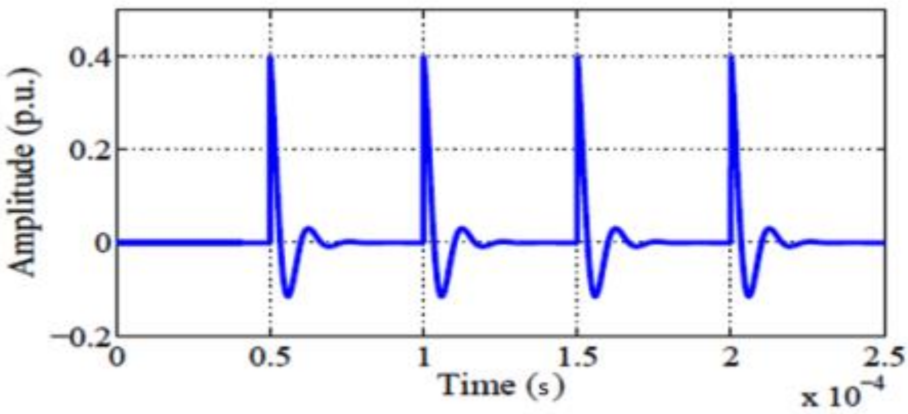


Fig. 2.5(a) Simulation of Train of pulses measured in RLC circuits

If input to the measurement circuit is given as an ideal step input and operational device is RLC, then the output voltage V(t) is damped oscillatory pulse(DOP) which is mathematically shown below

$$\boldsymbol{V(t) = Asin(2\pi ft)\left(e^{\frac{-t}{t1}} - e^{\frac{-t}{t2}}\right).u(t)} \qquad \mathbf{(2.1)}$$

From the above equation P gives peak value of the pulse,t_1,t_2 are the coefficients which are damping in nature,t_0 is the happening time and f is the frequency of the PD signal which one carrying 4 DOP type pulses shown in the above figure 2.5.Values of P and f are constant at 5 mV and 100 kHz. If input to the measurement circuit is given as an ideal step input and operational device is RLC, then the output voltage V(t) is damped exponentially pulse(DEP) which is mathematically shown below

$$\boldsymbol{V(t) = A\left(e^{\frac{-t}{t1}} - e^{\frac{-t}{t2}}\right).u(t)} \qquad \mathbf{(2.2)}$$

The sampling rate is 5 MHz To simulate noisy PD signals, the DEP and DOP type signals are noised by noise named as Gaussian noise at (SNR) value -10dB. The noisy DEP and DOP type signals generated after the addition of WGN are shown in Figure. To simulate PD signals severely buried by both noise and interference, the DEP and DOP type signals are corrupted by WGN at -5 dB and discrete spectral interference (DSI). Here the DSI is generated by the series combination of amplitude modulated signals described as

$$\boldsymbol{f(x) = \sum_{i=1}^{5}(a + m \times \sin(2\pi f_m t))\times sin(2\pi f_i t)} \qquad \textbf{(2.3)}$$

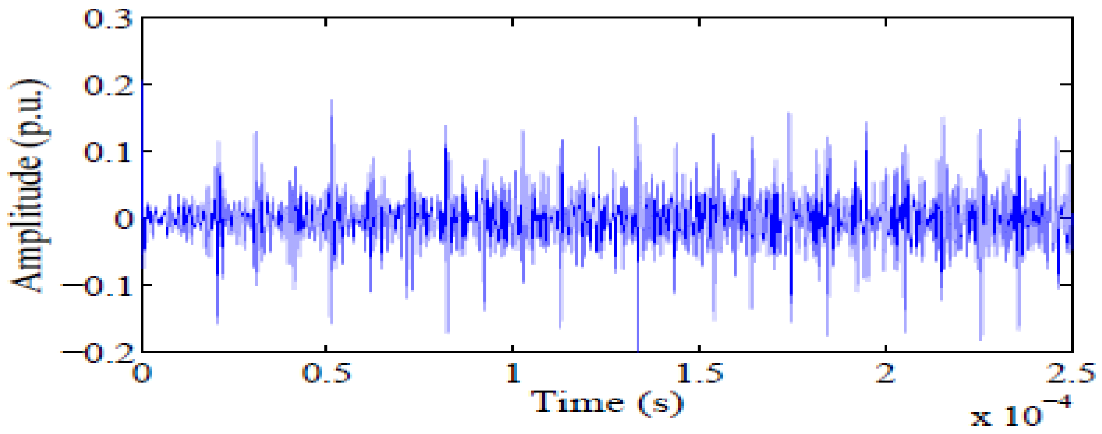


Fig. 2.6(b) Simulated noisy PD signals

From the above equation *a* is the amplitude of the carrier wave, *m* is the amplitude of modulating signal, f_i is the frequency of modulating signal, f_c is the frequency of the carrier wave. In this experiment various values of parameters are taken for the proper simulation The DSIs are obtained as modulated sine waves with 50% modulation .The WGN and DSI corrupted DOP type signals are shown above figure. In this thesis the DEP and DOP pulse type signals corrupted with WGN at SNR -5 dB are called the DEP type signal-1 and DOP type signal-1 respectively. The DEP and DOP type signals corrupted with WGN at SNR -10 dB and DSI are called the DEP type signal-2 and DOP type signal-2 respectively. A practical PD signal obtained using transformer oil as the dielectric specimen is shown in Fig. 2.5. Sampling frequency of the practical signal is 100 kHz.

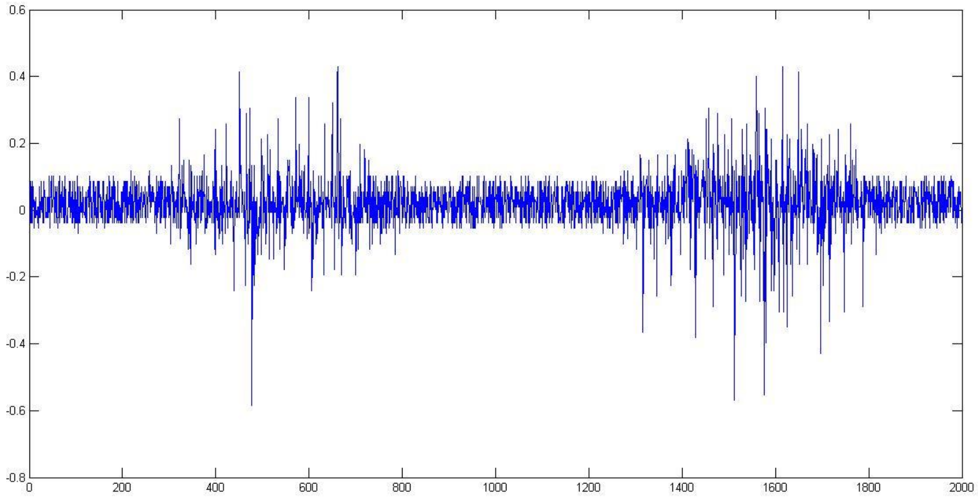


Fig. 2.7(a) Simulated Noisy PD pulse type signal obtained in high voltage laboratory

2.6 Summary

Using PD signal analysis, state of Insulation in HV power equipments can be analysed. During onsite and online PD measurements, noise and interference contaminate the recovered PD signal. Among the different de-noising techniques adopted to extract the PD signal, wavelet based techniques are superior. However, to determine the effectiveness of the wavelet based techniques it is required to evaluate the method by applying it on simulated noisy PD signals. The noisy PD signals are simulated numerically. By using the wavelet process it is not possible show the PD signals at different frequencies .So now a days we are using S-transform to show the time frequency spectrum of acquired PD signals. It eliminates the drawbacks of both STFT and WAVELET techniques. Modified S-transform filtering methods are successful for showing the time frequency (TF) resolution sharply. Here Wavelet based de-noising technique is applied to de-noise practical PD signals and then to represent that signal in TFR manner, S-transform is used. By the use of S-transform both time and frequency resolution can be known easily.

Chapter 3

De-noising of PD Signals using Discrete Wavelet Transform

Chapter 3

De-noising of PD Signals using Discrete Wavelet Transform

3.1 Introduction

PD measurements are performed onsite and online .The drawback of such measurement is that the acquired PD signal is corrupted by the surrounding noise and interferences. Hence the PD pulses to be analysed get buried in the severe noise. The large amplitude of amplitude modulation interference buries the signal inside it. Hence various time domain and frequency domain de-noising techniques are adopted to extract the PD pulses from such noise and interferences. Now a days wavelet transform came into view as a main tool for extraction of PD signals. Wavelet uses mother wavelet function as the main function which scales itself stated to frequency during analysis. This tool gives better result in comparison to STFT and FT because of using a wavelet on behalf of exponential function as window function. The aim of PD pulse signal de-noising is to retain the PD pulses and rejecting the noise and interferences. Using wavelet the noisy signal is decomposed into various frequency levels and stated as wavelet coefficients. The more similarity occurs between the wavelet and the PD structure, more is the coefficient's absolute value. So those coefficients which are of less magnitudes are thresholded to zero and the rest are retained. The modified coefficients are then used to rebuild the signal, which represents the de-noised PD signal. Wavelet is off two types,1-DWT,2-CWT.CWT based denoising is used for time signals which are continuous in nature and same as for DWT based denoising method for signals discrete in nature. DWT is more easy and efficient to process so DWT is used to de-noise the simulated and practical partial discharge (PD) signals.

3.2 Continuous Wavelet Transform (CWT)

Continuous Wavelet Transform (CWT) is employed for continuous time signals. It uses a wavelet as its basis function. The wavelet selected is called the mother wavelet. The scaled and transcribed kinds of the mother wavelet multiply with the signal for the denoising operation, to give wavelet coefficients at different decomposition levels. For a signal X(t) CWT can be expressed as

$$\boldsymbol{CWT(p,q) = \frac{1}{\sqrt{a}} \int_{-\infty}^{+\infty} X(t)\, g\left(\frac{t-q}{p}\right) dt} \qquad \textbf{(3.1)}$$

From above equation *p* tends to scale factor and *q tends to* translation factor. Both *p* and *q* are continuous in nature. *g(t)* is the mother wavelet being chosen. The scaling factor *p* is inversely related to frequency .That means if the frequency under analysis is high, then it flattens itself and if the frequency under analysis is small then it expands. The WT figures the signal *x(t)* to a two dimensional space. In accordance with the number of de-composition levels, the scaling factor p helps to divide the signal into different frequency levels.At a particular scale *p* the signal translates over continuous time to give wavelet coefficients .the main fruitful of the WT totally depends upon the selection of mother wavelet. There are such many wavelets present as like Daubechies, Morlet and Symlet. Among them the type Daubechies is most used type wavelet because of its performance that suits for the application in HV power system.

3.3 Discrete Wavelet Transform (DWT)

Wavelet analysis of a DT signal is calculated by DWT. Discrete wavelet transform procedure from CWT by replacing $p=p_0^m$ and $q= nq_0p_0^m$.

Now DWT of a discrete signal x[n] is defined mathematically given below

$$\boldsymbol{DWT(p,q) = \frac{1}{\sqrt{p_o^m}} \sum_n x[n] g\left[\frac{q-nq_0\, p_o^m}{p_o^m}\right]} \qquad \textbf{(3.2)}$$

Where, *g* represents the mother wavelet. *n* is an integer which shows the sample taken. Hence in DWT, *p* and *q* vary in a discrete manner. Likewise in CWT also scaling and translation process takes place in DWT as in terms of frequency range .DWT can be implemented using a quadrature mirror filters(QMF) which consists of both low pass filter *l[n]* and high pass filter *h[n]* (both are mirror phase to each other)which is shown in below figure. Take an example of signal x[n] is progressed into both LPFs and HPFs. Then the outputs which are taken from the filters are again down sampled by a factor 2 in order to get the dwt coefficients. The results secured after down sampling the output of high pass filter are known as detail coefficients and output from LPFs are called approximation coefficients. After that again that approximation coefficients are given to both HPFs and LPFs and the process is continued. Both thhe high pass and low pass filters are related by

$$\boldsymbol{h[L-1-n] = (-1)^n l[n]}$$

In above equation L represents the length of the filters. The filters are known as quadrature mirror filters (QMF).

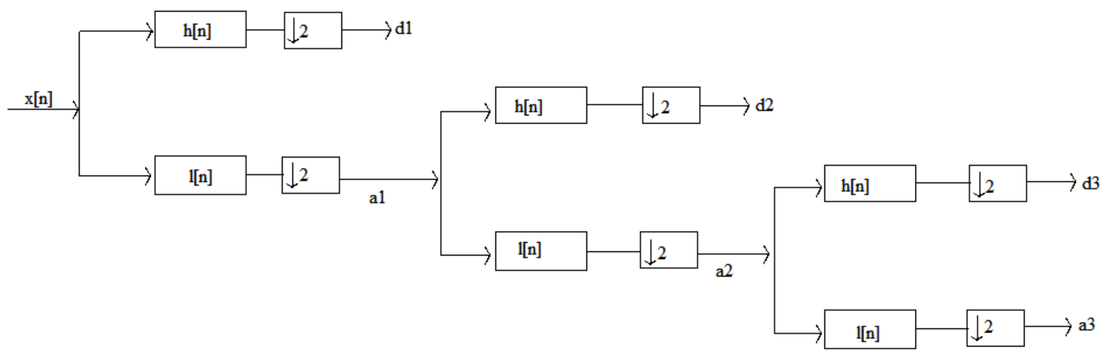


Fig. 3.1(a) Block diagram showing DWT decomposition Levels

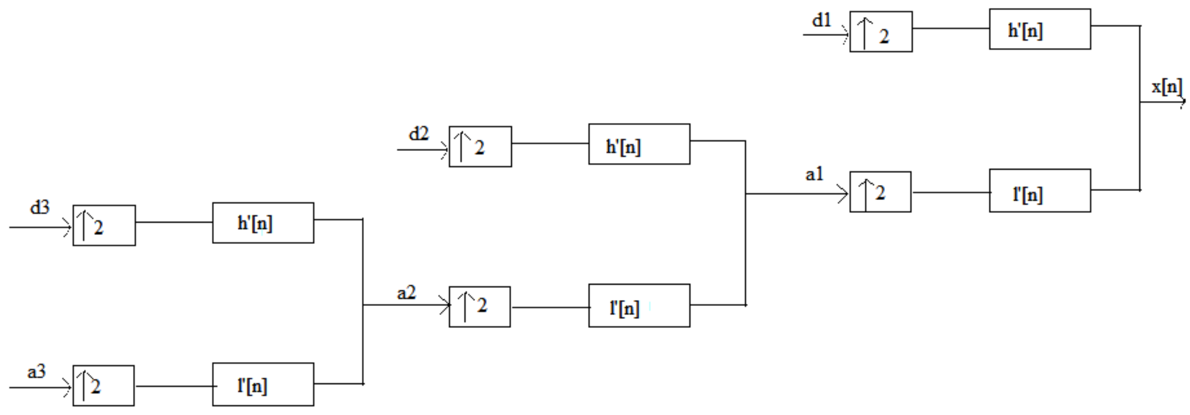


Fig. 3.2(b) Block diagram showing DWT reconstruction Levels

3.4. De noising of PD signals using DWT

DWT type denoising method results the DWT co-efficient for the stated signal, then by taking account of thresholding of the DWT which is followed by reconstruction of the same signal by the help of inverse wavelet of the modified DWT coefficients. Thresholding is of two types, 1-Soft Thresholding, 2-Hard Thresholding. Then to use Multi-resolution Signal Decomposition feature which is associated with DWT makes this possible to recover original signal coefficients and eliminating other sources .For the wavelet process to be happen for denoising of PD signals choice of some parameters has to be made. Such as selections of mother wavelet, choice of decomposition level, selection of thresholding function are main issues in the execution of DWT.These are discussed below.

3.4.1 Selection of mother wavelet

DWT based de-noising results totally depends upon the selection of mother wavelet. The wavelet shows better de-noising results if its shape and size similar to that of original PD signals that has to be extracted. Choice of mother wavelet is scale independent. Two different type of wavelet selection is used,1-scale independent,2-level dependent .In the 1^{st} case single wavelet is used for all decomposition levels ,In 2^{nd} case for each level mother wavelet is to be. There are different types wavelet tools presented, among them db2 (Daubechies wavelet of order 2), db7 (Daubechies wavelet of order 7) is mostly used, because of giving most appropriate result.

3.4.2 Selection of maximum decomposition level

In DWT maximum decomposition level of a signal is calculated by $J_{ul.}$ =fix ($\log_2 n$)

Where n is the signal length, ‘fix ‘results the value in the bracket given to nearest integer. But in this work wavelet toolbox is used, the signal at the highest level of decomposition might not be smaller than the width of the wavelet filter which is used.

3.4.3 Selection of thresholding rule

This is the crucial part in wavelet based PD signal denoising, because it functions crucial role in the rejection of the noisy coefficients and improves the accuracy of the denoising results.

The various thresholding rules are taken for wavelet denoising process. These are given below.

1-Automative thresholding rule

2-Reconstruction based thresholding rule

3-Visual inspection based thresholding

Two types of thresholding used in Wavelet denoising process.

a. Hard Thresholding:-

Hard thresholding sets the data in such a manner that wavelet coefficients are picked those are greater than the threshold value, remaining coefficients tends to zero.

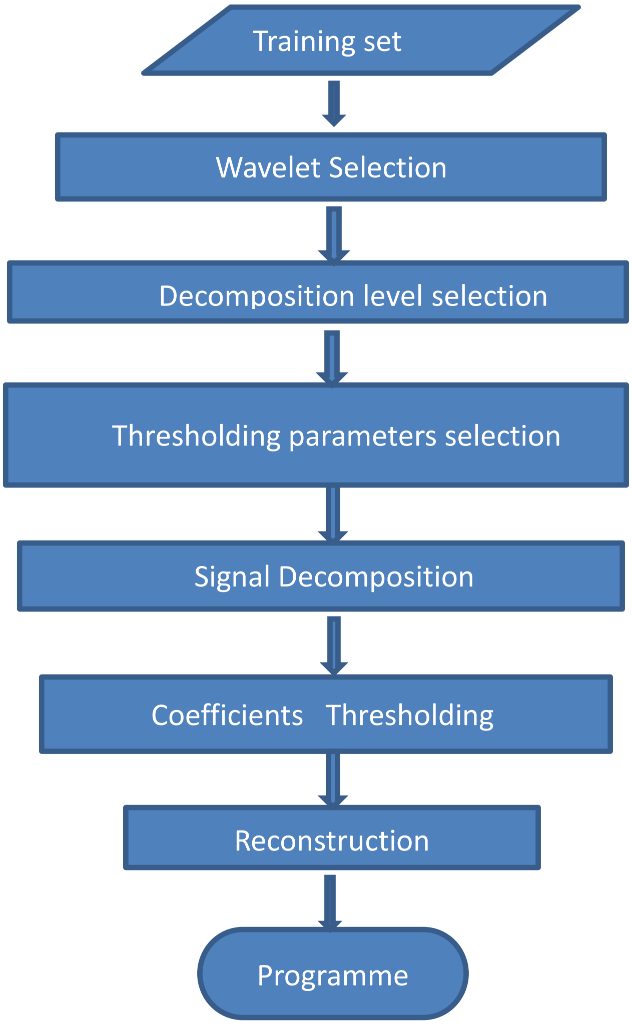
b. Soft Thresholding:-

Soft thresholding sets the wavelet coefficients which is below the threshold to null.The coefficients which are greater than threshold are picked, remaining decrease towards zero

The following flowchart shows the total procedure of wavelet analysis of PD signal

Discrete wavelet transform (DWT) is an important denoising technique for partial discharge (PD) signals. DWT of a signal is taken out using various techniques depending on the methods of mother wavelet selection, thresholding rule and the maximum decomposition level. The de-noising method to be applied on a noisy signal depends on the kind the PD pulse to be extracted and severity of noise and interference. It is seen that for excessively noisy signal reconstruction based thresholding produce better result than automatic thresholding rule. And when both the methods fail, visual inspection based thresholding can denoised a PD signal.

3.4.4 Flowchart



3.4.5 DWT based de-noising results of PD signals

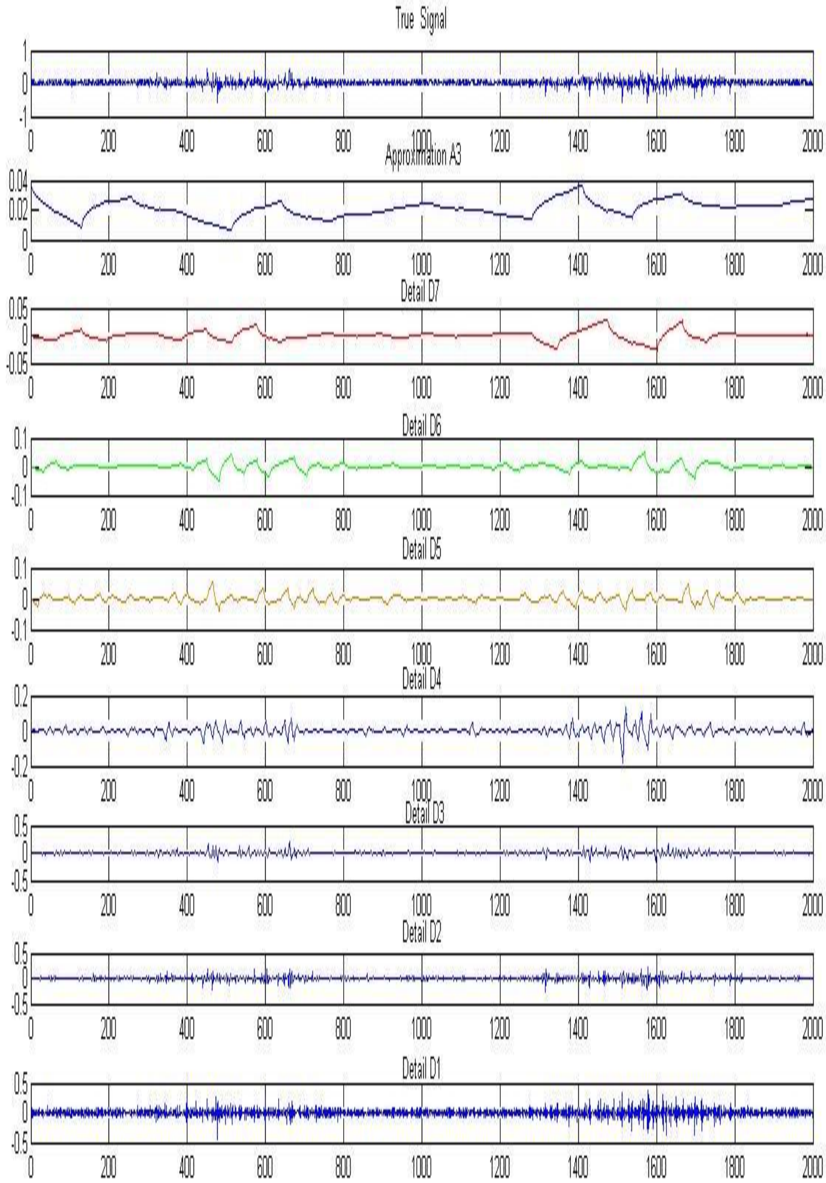


Fig. 3.3 (a) DWT coefficients (D1-D7, A3) decomposed up to level 7 using db2 mother wavelet

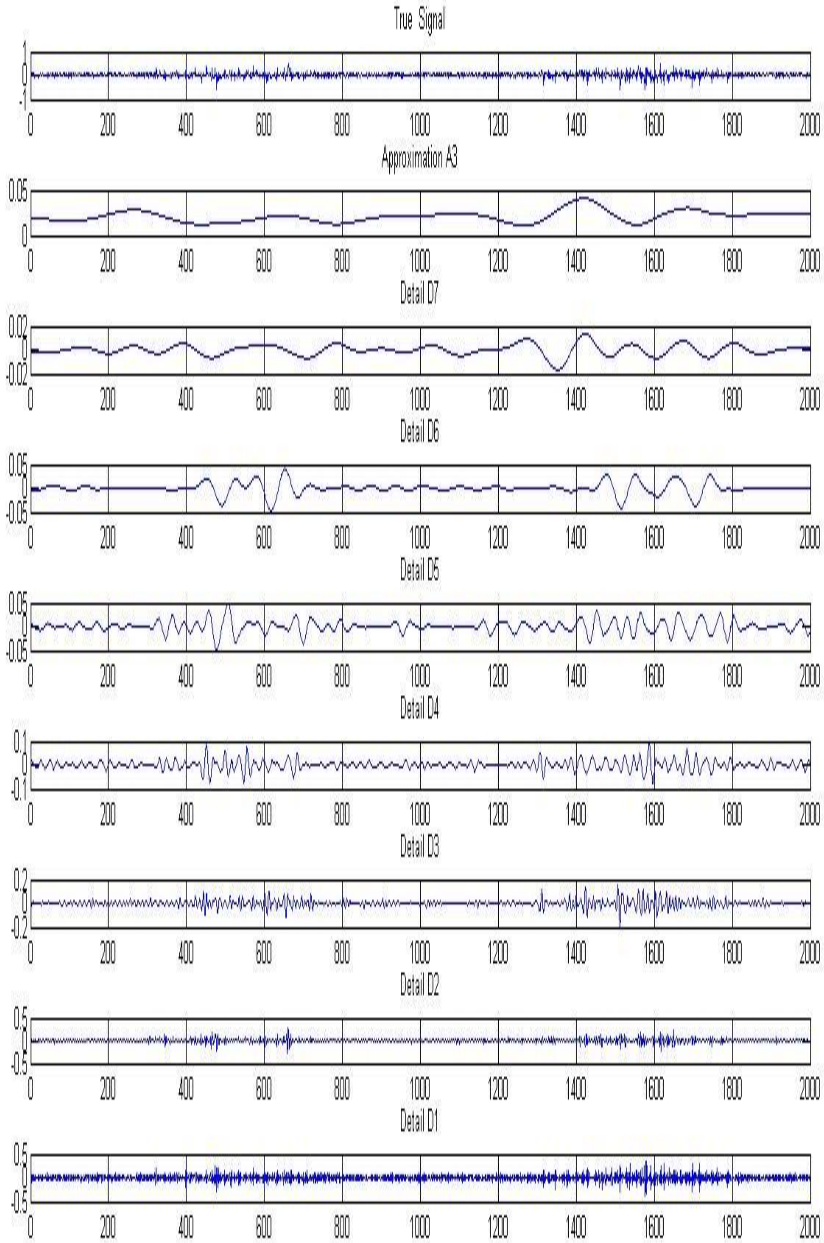


Fig. 3.4 (b) DWT coefficients (D1-D7, A3) decomposed up to level 7 using db7 mother wavelet (Morlet thresholding)

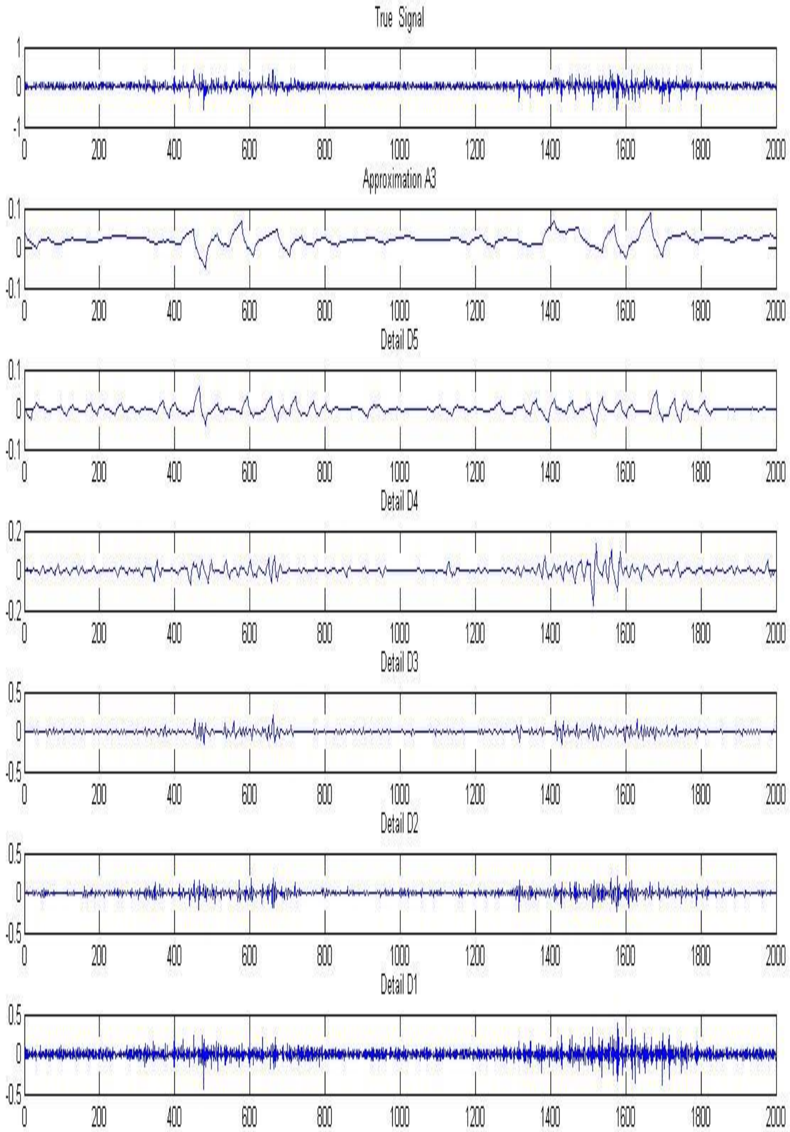


Fig. 3.5 (a) DWT coefficients (D1-D5, A3) decomposed up to level 7 using db2 mother wavelet

(Soft thresholding)

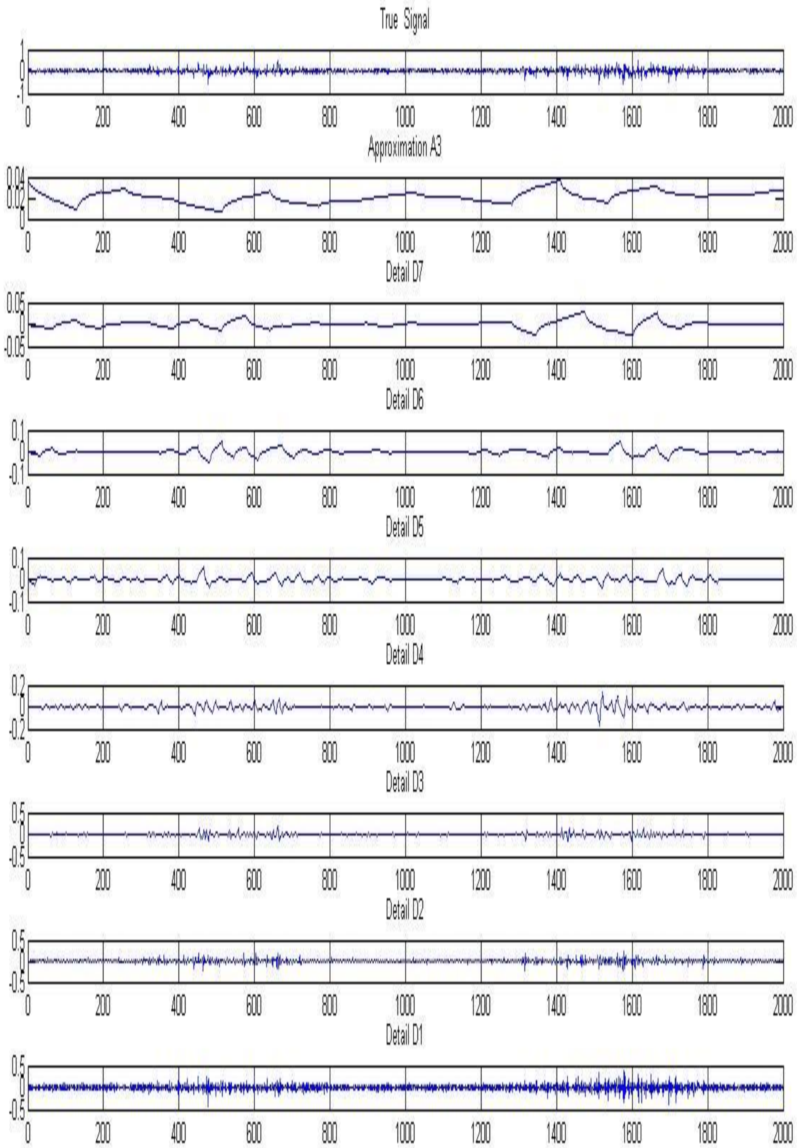


Fig. 3.6 (b) DWT coefficients (D1-D7, A3) decomposed up to level 7 using db2 mother wavelet

(Hard thresholding)

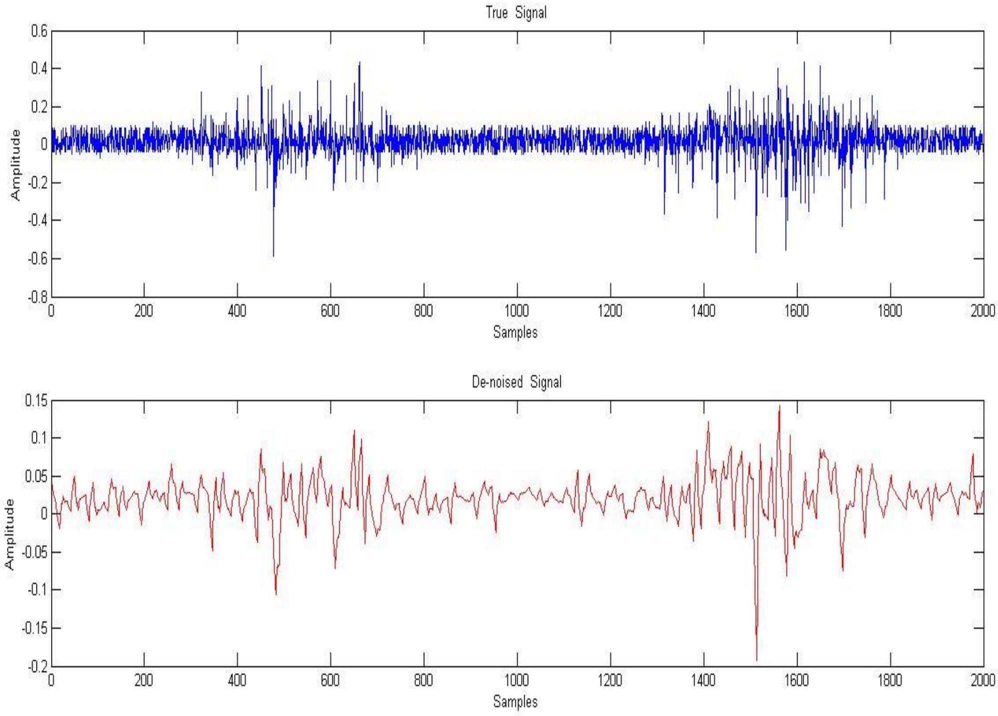


Fig. 3.7 (a) DWT based denoising using db2 type mother wavelet

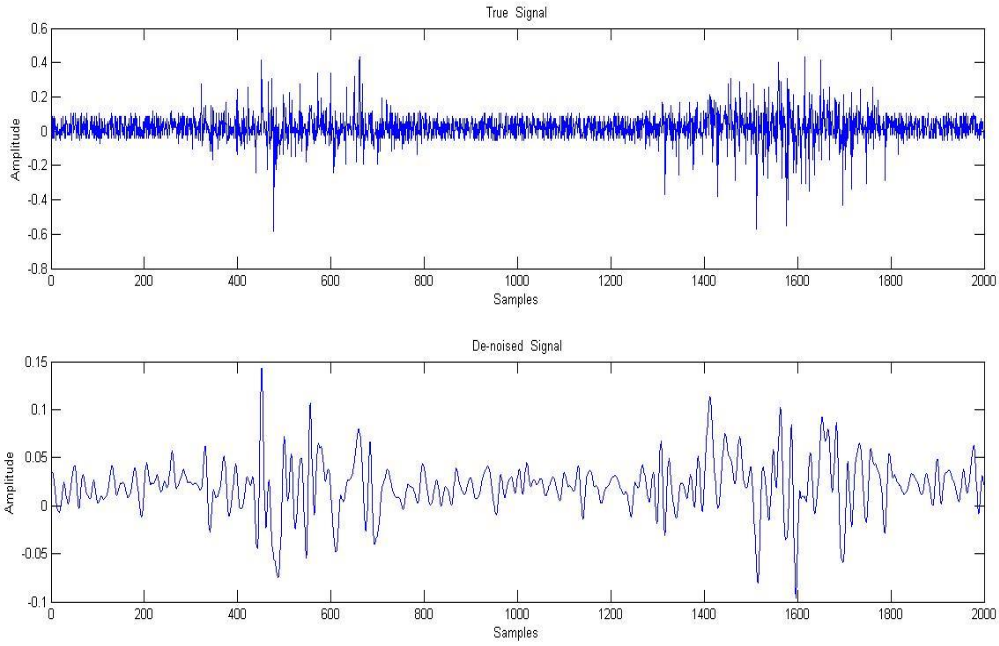


Fig. 3.8 (b) DWT based denoising using db7 type mother wavelet

3.4.6 Summary

Discrete wavelet transform (DWT) is an important denoising technique for partial discharge (PD) signals. DWT of a signal is taken out using various techniques depending on the methods of mother wavelet selection, thresholding rule and the maximum decomposition level. The de-noising method to be applied on a noisy signal depends on the kind the PD pulse to be extracted and severity of noise and interference. It is seen that for excessively noisy signal reconstruction based thresholding produce better result than automatic thresholding rule. And when both the methods fail, visual inspection based thresholding can denoised a PD signal.

Chapter 4

Stockwell Transform

Introduction

Continuous S-Transform

Discrete S-transform

Application of S-transform to PD Signal Analysis

Summary

Chapter 4

Stockwell Transform

4.1 Introduction

In the time frequency analysis field short time Fourier Transform (STFT) gives TFR of a time series signal. In order to manipulate STFT, a window function is used which familiarise time and frequency. But the main problem occurs in STFT is fixed width of window function, for that reason STFT gives poor time frequency resolution On the other hand wavelet uses a basis function for dilation and contraction, Still it is a best tool for signal analysis but it is unable to give phase information and visual analysis of the signals. In order to overcome drawbacks of both STFT and WAVELET new time frequency representation developed by R.G.Stockwell by taking features of both STFT and WAVELET know as Stockwell transform. It is the hybrid version of phase corrected WAVELET and better resolution STFT which uses a window of variable width and uses phase kernel in order to show phase information the signals and supplementary information about spectrum. Now a days an updated version of S-transform called as modified S-transform. Here also modified S-transform used for realization of signals.

4.1.1 The Continuous *S*-Transform

The S-transform is a time frequency representation (TFR) process which is proposed by Mansinha et al. holds characteristics of STFT and Wavelet Transform (WT). It gives the result about frequency resolution which must be dependent. By maintaining a constant relation with Fourier transform spectrum. Suppose a continuous signal defined as x(t),by taking the S-transform of that signal which is shown below.

$$\boldsymbol{st(\tau, f) = \int_{-\infty}^{\infty} h(t) g(\tau - t) e^{-j2\pi f t} dt} \qquad (4.1)$$

$$\boldsymbol{s(\tau, f) = \int_{-\infty}^{\infty} X(\alpha + f) e^{-\frac{2\pi\alpha^2}{f^2}} e^{-j2\pi\alpha\tau} d\alpha} \qquad (4.2)$$

Equation 4.2 is applicable for every signal for time frequency presentation, where α shows the width of the window

Here τ and f shows the localization spectral time and spectrum frequency and $g(t)$ denotes a window function.

$$\boldsymbol{g(t) = \frac{|f|}{\sqrt{2\pi}} e^{-\frac{t^2 f^2}{2}}} \qquad (\mathbf{4.3})$$

From the above equation it is finally known that S-transform is one the particular case of STFT with Gaussian function. If the gaussian window length in S-transform in larger in time domain then frequency resolution will be better at lower frequency, same occurs in the opposition case if the length of the gaussian window is smaller , then time resolution is better at higher frequency.

4.1.1.1 S -Transform and CWT

The expression of the Continuous Wavelet Transform (CWT) is

$$\boldsymbol{W(\tau, d) = \int_{-\infty}^{\infty} h(t) w(t - \tau, d) dt} \qquad (\mathbf{4.4})$$

Here t=time, h (t) = time series, τ=times of spectral limit, d=wavelet width, w(t,d)=scaled version of mother wavelet which acquires zero mean of zero value.

S transform is a special case of CWT with a particular mother wavelet multiplied by the phase factor, which is shown below

$$\boldsymbol{S\ (\tau,f) = e^{-j2\pi f t} W(\tau, d)} \qquad \textbf{(4.5)}$$

d stands for inverse of the frequency *f.*

From above expression it is concluded that S-transform also maintains direct relation with Fourier transform spectrum. Where $\boldsymbol{W(\tau, d)}$ is the mother wavelet.

$$w(t) = \frac{|f|}{\sqrt{2\pi}} e^{-\frac{t^2 f^2}{2}} e^{-j2\pi ft} \qquad (4.6)$$

So it is found here that wavelet does not following zero mean.

S-transform is also related with STFT

$$S(\tau, f) = STFT(\tau, f) = \int_{-\infty}^{\infty} h(t) \frac{|f|}{\sqrt{2\pi}} e^{-\frac{(\tau-t)^2 f^2}{2}} e^{-j2\pi ft} dt \qquad (4.7)$$

If the *S*-transform gives representation of the local spectrum, there is direct relation exist between the *S*-transform and Fourier transform.

4.1.2 Discrete S-Transform

Let *h[kT]*,k=0,1,….N-1 gives discrete time series corresponding to the continuous signal h(t) with an interval T which is sampled. The DFT is shown as

$$H\left[\frac{n}{NT}\right] = \frac{1}{N} \sum_{K=0}^{N-1} H[kT]\, e^{-\frac{j2\pi mk}{N}} \qquad (4.8)$$

So S-transform of the discrete time series *h[kT]* is shown below,

(Take *f* tends to *n / NT* ,and τ tends to *jT*)

$$S\left[iT, \frac{n}{NT}\right] = \sum_{m=0}^{N-1} H\left[\frac{m+n}{NT}\right] e^{-\frac{2\pi^2 m^2}{n^2} e^{\frac{j2\pi mk}{N}}}, n \neq 0 \qquad (4.9)$$

Where i, m, and n=0,1,…. N-1.For n=0, S-Transform changed as

$$S[jT, 0] = \sum_{m=0}^{N-1} H\left[\frac{m}{NT}\right] \qquad (4.10)$$

Then inverse of the discrete S-transform is

$$\boldsymbol{H}[\boldsymbol{kT}] = \sum_{\boldsymbol{m}=\boldsymbol{0}}^{\boldsymbol{N-1}} \left\{ \frac{\boldsymbol{1}}{\boldsymbol{N}} \sum_{\boldsymbol{j}=\boldsymbol{0}}^{\boldsymbol{N-1}} \boldsymbol{S}\left[\boldsymbol{jT}, \frac{\boldsymbol{n}}{\boldsymbol{NT}}\right] \right\} \boldsymbol{e}^{\frac{\boldsymbol{j2\pi mk}}{\boldsymbol{N}}} \qquad (\mathbf{4.11})$$

The output of ST is a $k \times n$ matrix whose rows tends to frequency and columns tends to time. This matrix represents the original PD pulse in different manner. Apart from use of S-transform there is a problem associated with this transform which tends to reduction of the time resolution of experiment onsets as well as offsets .This agonizes from very small energy values in the time and frequency domain. In order to avoid these problems, generalized S-transform proposed by Mc.Fadden et al. shows a better control of the window function and which are non-symmetrical in nature for both time and frequency resolution. It will take several different Gaussian windows which are varying in shape and scale, provide an improvement in time frequency representation (TFR) of the signals. The improvement is controlled by introducing a scaling function in S-transform which controls sharply width of the window function.

To calculate the discrete S-transform, we use following steps such as

1) Manipulate the DFT of given time series h (kT) taking an account of N points and also sampling interval T to get $H\left[\frac{m}{NT}\right]$ by the use of FFT.
2) Manipulate Gaussian window function H [m,n] for the given frequency n / NT.
3) Shift that spectrum $H\left[\frac{m}{NT}\right]$ to $H\left[\frac{m+n}{NT}\right]$ for the same frequency n / NT .
4) Multiply H[m,n] by $H\left[\frac{m+n}{NT}\right]$ to get the result in matrix form.
5) Take the inverse Fourier transform of that result according to the frequency $\frac{n}{NT}$.
6) Repeat the above steps till rows of S-transform to every frequency $\frac{n}{NT}$ have been calculated.

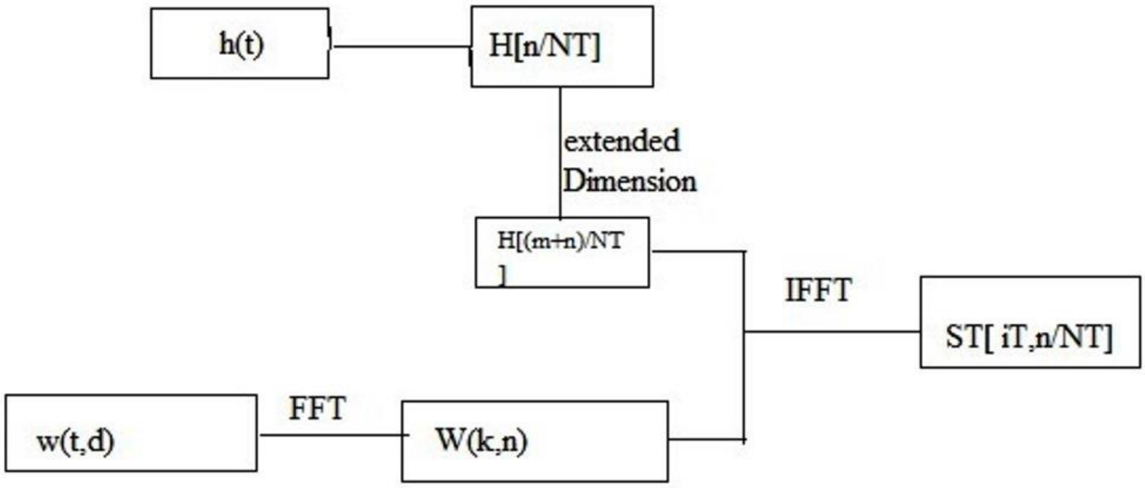


Fig. 4.1 (a) Flow Chart for Stockwell Transform

4.1.3 Application of S-transform to PD Signal Analysis

$$\boldsymbol{s(\tau, f)} = \int_{-\infty}^{\infty} \boldsymbol{X(\alpha + f) e^{-\frac{2\pi\alpha^2}{f^2}} e^{-j2\pi\alpha\tau} d\alpha} \quad (\mathbf{4.2})$$

By using the above equation we can represent the PD signals in time frequency manner by the use of S-Transform. Total plot depends upon the factor α, as it controls both time and frequency resolution during transform operation. If the value of α is small then it shows high time resolution, same happens in opposite case, if α value is high tends to high frequency resolution.

Time Frequency Representation of PD signal

In this chapter Time Frequency Representation (TFR) of a signal could be analysed by the use of S-transform. The representation shows the frequency component information and location of these components in the given signal. The practical partial discharge (PD) signals is also observed using S-transform. It is observed that the WT denoising technique using mother wavelet selection method and automatic thresholding rule gives better result of the practical noisy PD signals .But in S-Transform only noisy and denoised PD signals can be represented by their time frequency presentation with different resolution. For the low value of α frequency resolution of the experimented PD signal is poor, still time resolution is good. Hence, the value of is increased from 1 to higher values to show good frequency resolution.

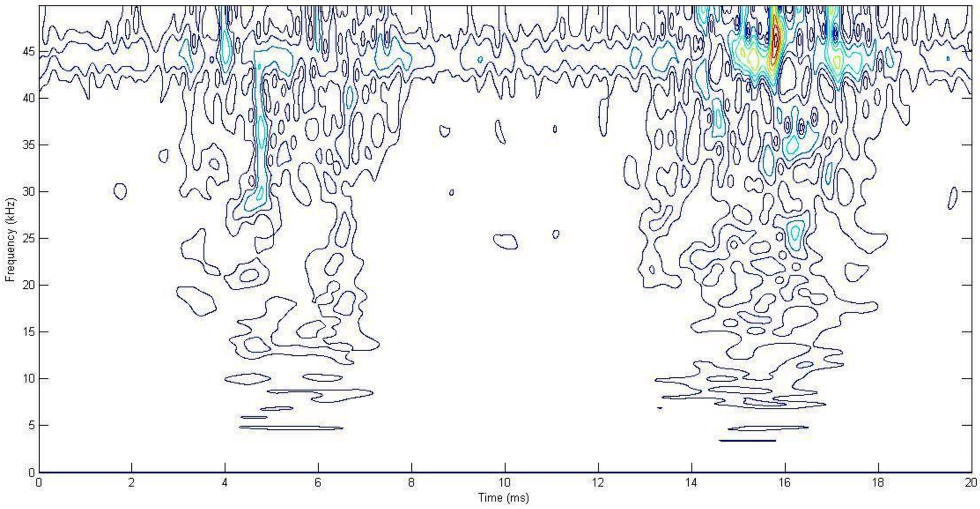


Fig. 4.1(a) S-transform contour of the noisy practical PD signal

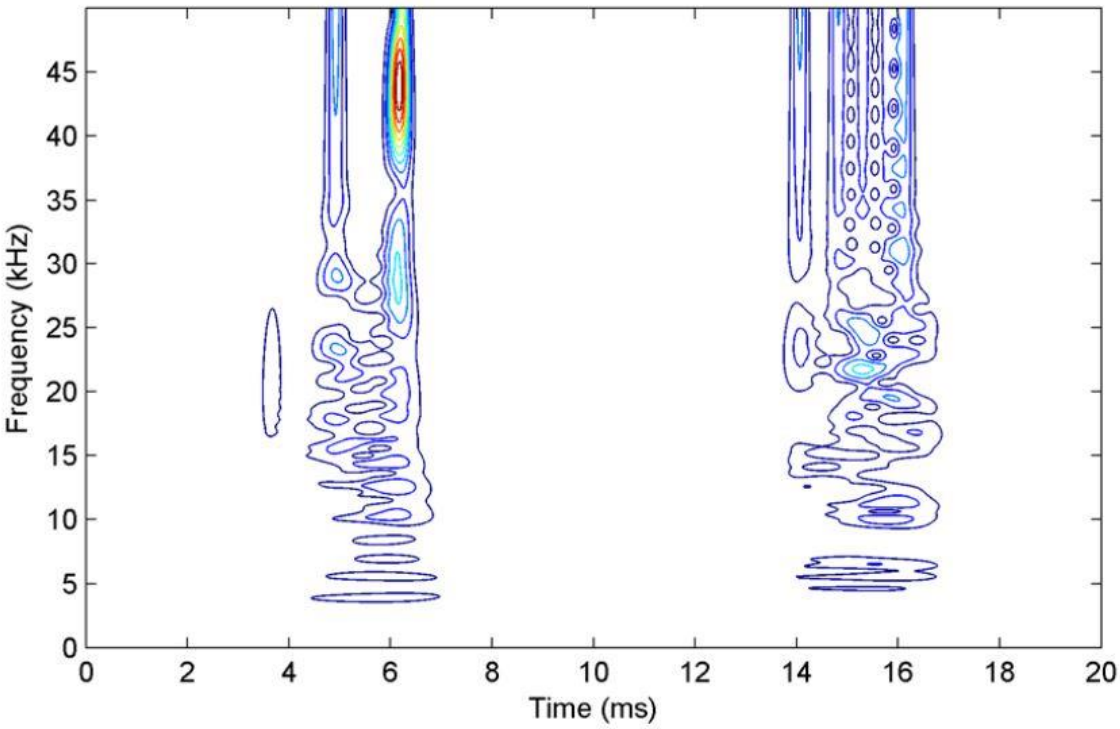


Fig. 4.2 (b) S-transform contour of the de-noised practical PD signal for α =4

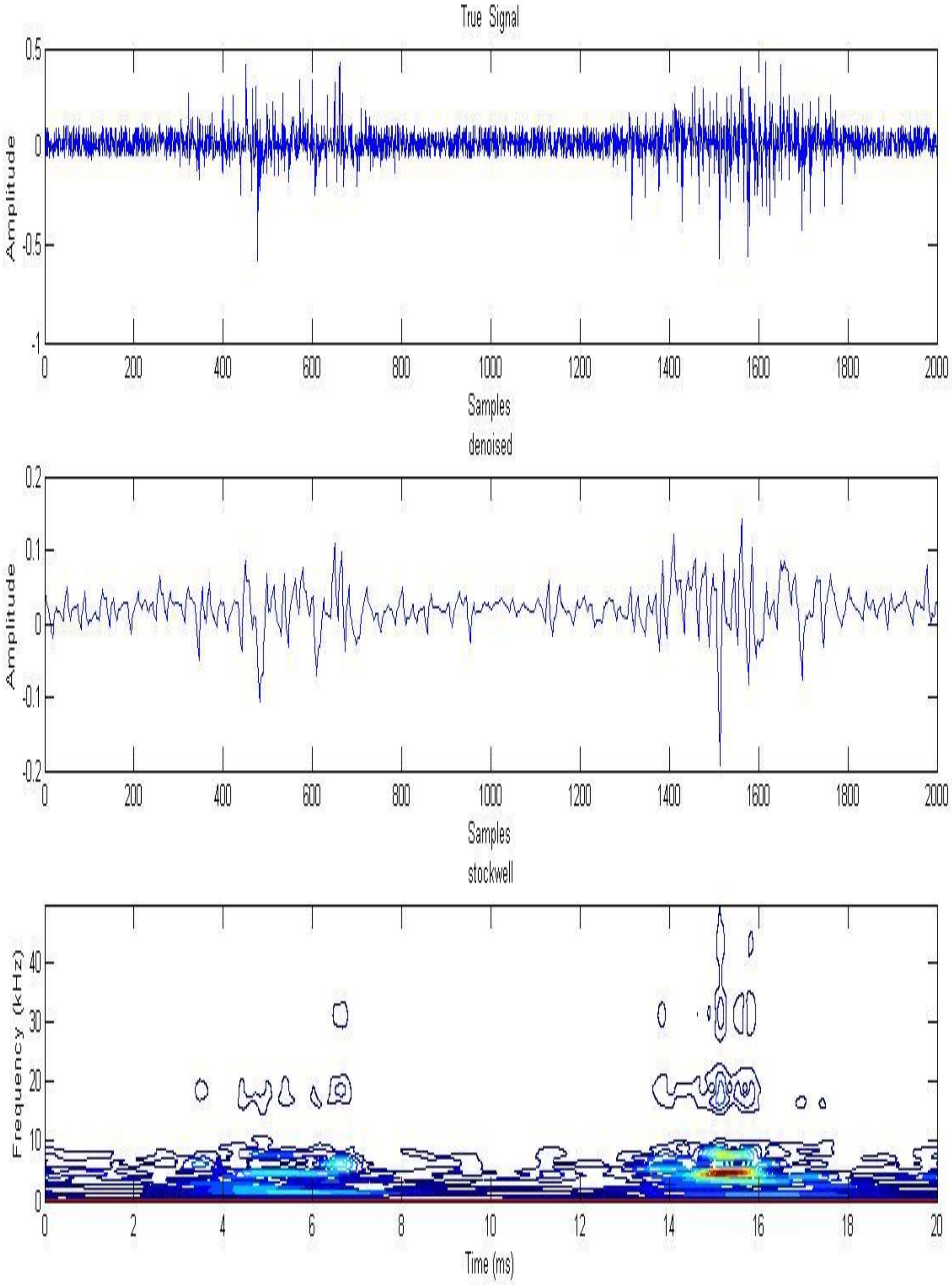


Fig. 4.3 (a) S-transform contour of (db2) denoised PD signal (α =1)

Discussion

It is seen in the figure that, as the value of the factor α increases, the frequency resolution of the signal improves. It is also seen in the figure that, as the value of the factor α decreases, the time resolution of the signal improves. It is clearly shown that spike of the denoised PD signal is represented as small circle in the S-contour.

4.1.4 Summary

S-transform has emerged as an efficient tool for time-frequency representation (TFR) of any type signal. From this chapter S-Transform theory is presented. At first the given noisy is denoised by Wavelet process and that extracted denoised signal is represented by using S-transform for TFR .In S-transform the factor α is varied to regulate the frequency resolution of the TFR of the signal. S-transform shows better time frequency resolution. The standard S-transform results perfect time resolution at high frequency but fails in low frequency and good frequency resolution at low frequency but smears in higher frequency as seen from the time-frequency representation.

Chapter 5

Conclusion and Scope for Future Work

Chapter 5

Conclusion and Scope for Future Work

5.1 Conclusion

Onsite and online PD measurements, the PD signals are put in excessive noise and interferences. Hence, the main work is to extract original PD pulses from noisy PD pulses by eliminating the noises. For this Wavelet technique is used to do this process and successfully it conquered noises and gives somewhat PD pulses. Wavelet method follows certain parameters like decomposition rules, threshold selection method, type of threshold rule etc. But in wavelet it is unable to show time frequency presentation .So S-transform is introduced in order to eliminate drawbacks of wavelet techniques. It is emerged as an efficient tool for time-frequency representation (TFR) of any signal. In this thesis, first the given noisy signal is denoised by Wavelet process and that extracted denoised signal is analysed by using S-transform for TFR .In S-transform the factor α is varied to regulate the frequency resolution of the TFR of the signal. S-transform shows better time frequency resolution. By these methods we can analyze the characteristics of PD pulses, so that it is easier to monitor PD pulses from HV electrical apparatuses.

5.2 Scope for future work

Denoising of PD signal is the main problem occurs in partial discharge signal analysis. Once the signal is extracted from severe noise and interference, it can be analysed. Wavelet analysis is a strong tool for denoising the Partial Discharge signals. Wavelet analysis of a signal can be happened using discrete wavelet transform(DWT) and performing wavelet transform, each of which depends on the mother wavelet chosen, maximum decomposition level chosen and the selection of thresholding rule. This work compares the different de-noising techniques applied to PD signals having different characteristics and it is seen that a more effective wavelet based de-noising technique is required which can be applied to all types of PD signals irrespective of their characteristics. Also modified S-transform will be applicable for analysis of PD signals at particular time and frequency and detect the PD signals. More research is going on PD signals for denoised and TFR spectrum.

5.3 References

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